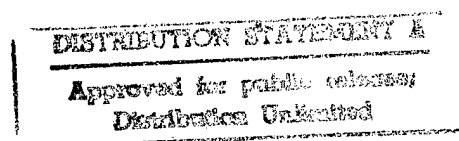PERFORMANCE REPORT
A Cockroach-Like Hexapod Robot
for Natural Terrain Locomotion

Period of Performance: 3 Years

Starting Date: January 1, 1996

December 18, 1996

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Research Progress

The kinematic configuration and joint degrees of freedom for Robot III have been designed based upon motion studies of cockroach walking on smooth terrain and over barriers: 3 articulated joints (2 active) in the rear legs, 3 or 4 degrees of freedom in the middle leg, and 4 or 5 degrees of freedom in the front leg. The rear legs are used primarily to drive the cockroach, the middle legs are used for support and turning and to lift the body during climbing, and the front legs are typically used as sensors to help find footholds in climbing. A CAD model of the robot has been developed to help us design its overall structure (see figures). The weight of the robot should be under 20 lbs.

A prototype front leg with 4 degrees of freedom has been completed including pneumatic actuators and servo valves and potentiometers at each joint. Servo control software was developed to control this leg using pulse-width-modulation and proportional control. The leg was shown to follow cockroach-like motions with the necessary controllability and repeatability. However this prototype front leg has two drawbacks: it does not have a range of motion equivalent to that of the cockroach's front leg (in fact it is appropriate for the middle leg) and its tibia actuator tends to contact the ground during walking.

A second prototype front leg has been developed including five degrees of freedom. These degrees of freedom have been shown to be sufficient for cockroach-like front leg motion in simulation. The new prototype is also lighter and the ground contact problem has been eliminated by incorporating the tibia actuators into the femur structure.

A locomotion controller has been developed for the K2T robot based on our Robot II controller. A distributed gait controller has been developed based upon the mechanisms thought to coordinate the legs of the stick insect. The individual leg controllers include vertical compliance and the elevator reflex for locomotion on rough terrain. A controller mechanism has been added so that the robot can turn at varying radii independent of its speed. The simulated robot walks on rough terrain given a commanded speed and direction of motion. Its gait changes with its speed and turning radius. The gait controller has been installed in the K2T robot and preliminary results show that it performs as expected.

An exhaustive characterization of the kinematics of joint movement and its relationship to electromyogram (EMG) data for mesothoracic and metathoracic legs during free walking on a treadmill has now been completed. Many of the results were as expected, such as the correlation

between Ds activity and joint velocity. However, many other factors were surprising and actually raised some new questions. For example, the role of fast motor neurons in extension of the CF and FT joint movement as the animal runs faster is not completely clear. Joint velocity does not increase dramatically when these fast motor neurons are recruited. However, the transition period from flexion to extension is significantly decreased, suggesting that fast motor neurons may act to increase stiffness in the joint, thereby decreasing transition time. This may be a property that can be exploited in robotic design.

We subsequently extended this analysis to the front legs. The movements of these legs is sufficiently complex as to make analysis of their movements very difficult. Our observations to date are that the specific joint movements of the front legs actually move in antiphase with the homologous joints of the hind and middle legs. Thus, SETi extends the FT joint during swing for the front leg but is a major part of the stance phase for the other legs. Ds often fires two bursts during the stance phase. These observations underscore the conclusion that the roles of the three pairs of legs are very different. This conclusion is based both on Robert Full's data on ground reaction forces and our own data. Our current notion is that the role of the hind legs is to provide power. The middle legs are primarily involved in changes in direction of movement and attitude of the body (during climbing). The front legs seem to have much more variability of movement in three dimensions, making them excellent for their role as sensory-motor appendages used to investigate the surrounding terrain.

We have also begun to analyze leg movements used in climbing over a barrier. In order to execute a climb, the animal first changes attitude of the body by rotating the middle leg so that its tibia is more perpendicular to the substrate. The front legs then locate the top of the object to be scaled. Finally, the hind legs thrust back normally to force the animal up and over the barrier. We are currently beginning to investigate the motor neuron activity used to control these movements. The results of all of these efforts are being used in the design of Robot III.

Further studies were carried out of model central pattern generators (CPGs) for walking that were previously evolved using genetic algorithms. These studies revealed that the best evolved CPG could be understood using a technique that we call transition analysis. This technique relies on the fact that the outputs of most neurons in this evolved circuit are in saturation most of the time, with only one neuron at a time typically making a transition. This idea was placed on a solid mathematical basis using the tools of dynamical systems theory, allowing us to quantitatively predict when transitions will occur and how long they will take. This analysis has also suggested a technique for designing pattern generators that exhibit a desired sequence of

transitions, each of which take a specified amount of time. We are currently studying the scope of applicability of transition analysis and its evolutionary implications by statistically analyzing a large set of evolved CPGs. In addition, we are trying to extend transition analysis to situations in which more than one neuron makes a transition at one time.

Publications

Beer, R.D. (1996). Toward the evolution of dynamical neural networks for minimally cognitive behavior. In P. Maes, M. Mataric, J. Meyer, J. Pollack and S. Wilson (Eds.), *From Animals to Animats 4: Proceedings of the Fourth International Conference on Simulation of Adaptive Behavior* (pp. 421-429). MIT Press.

Beer, R.D., Quinn, R.D., Chiel, H.J., and Ritzmann, R.E. (in press). Biologically-inspired approaches to robotics. To appear in *Communications of the ACM*.

Beer, R.D. and Chiel, H.J. (in press). Commentary on "A simple neural network for the control of a six-legged walking system" by Cruse et al. To appear in P. Crago and J. Winters (Eds.), *Biomechanics and Neural Control of Movement*.

Chiel, H.J. and Beer, R.D. (1996). Testing the cellular reduction hypothesis in model neural circuits. *Soc. Neurosci. Abstr.* **22**:133.

Chiel, H.J. and Beer, R.D. (in press). Commentary on "Biomechanics of hydroskeletons: Lessons learned from studies of crawling in the medicinal leech" by Kristan et al. To appear in P. Crago and J. Winters (Eds.), *Biomechanics and Neural Control of Movement*.

Dellaert, F. and Beer, R.D. (1996). A developmental model for the evolution of complete autonomous agents. In P. Maes, M. Mataric, J. Meyer, J. Pollack and S. Wilson (Eds.), *From Animals to Animats 4: Proceedings of the Fourth International Conference on Simulation of Adaptive Behavior* (pp. 393-401). MIT Press.

Nelson, G.M., Quinn, R.D., Watson, J.T., Tryba, A.K., Ritzmann, R.E., Chiel, H.J. and Beer, R.D. (1996). Simulated dynamics of walking and climbing in the cockroach. *Soc. Neurosci. Abstr.* **22**:1077.

Watson, J.T., Tryba, A.K. and Ritzmann, R.E. (1996). Analysis of prothoracic leg movement during walking and climbing in the cockroach. *Soc. Neurosci. Abstr.* **22**:1077.

Submitted

Chen, C. T., Quinn, R. D., Ritzmann, R.E. (submitted). A crash avoidance system based upon the cockroach escape response circuit, submitted to the 1997 IEEE International Conference on Robotics and Automation (ICRA '97).

Nelson, G. M., Quinn, R. D., Bachmann, Flannigan, W. C., Ritzmann, R. E., Watson, J. T. (submitted). Design and simulation of a cockroach-like hexapod robot, submitted to the 1997 IEEE International Conference on Robotics and Automation (ICRA '97).

Vaidyanathan, R., Chiel, H. J., and Quinn, R. D. (submitted). A hydrostatic robot for marine applications, submitted to the 1997 IEEE International Conference on Robotics and Automation (ICRA '97).

Watson, J.T. and Ritzmann, R.E. (1996). Leg kinematics and muscle activity during treadmill running in the cockroach, *Blaberus discoidalis*: I. Slow running. Submitted to *J. Comp. Physiol.*

Watson, J.T. and Ritzmann, R.E. (1996). Leg kinematics and muscle activity during treadmill running in the cockroach, *Blaberus discoidalis*: II. Fast running. Submitted to *J. Comp. Physiol.*

Presentations

R. Beer gave an invited talk at the conference on "Dynamical Neuroscience: Traversing Scales of Organization", Washington, D.C., November 15-16, 1996.

R. Beer gave an invited seminar at University of Michigan, Ann Arbor, Oct., 1996.

R. Beer gave an invited talk at the ONR contractors meeting, Boston University, July 10-12, 1996.

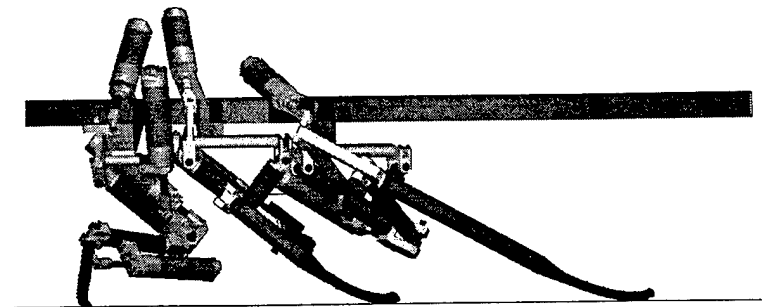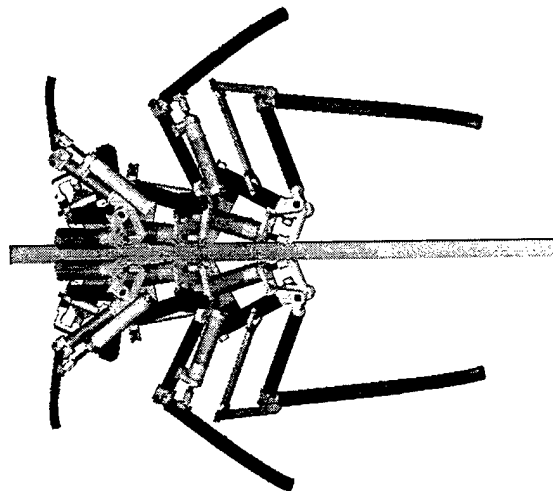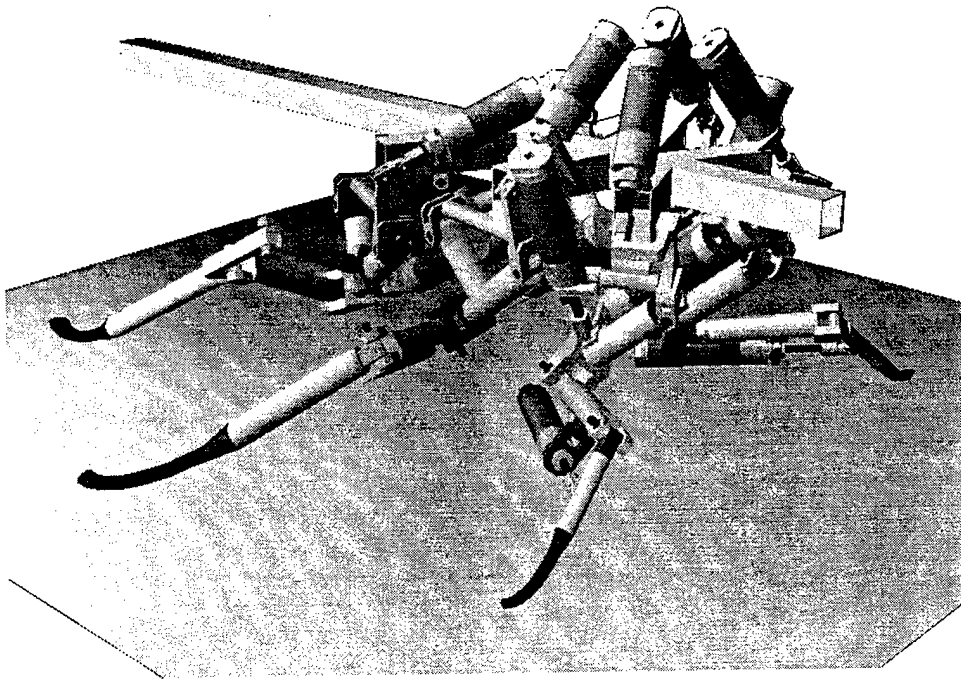H. Chiel gave an invited seminar at Brandeis University, Oct., 1996.

H. Chiel gave an invited talk at the AI Lab, MIT, Oct., 1996.

R. Quinn gave an invited talk at the Autonomous Robotic Systems for U.S. Navy Littoral Operations Workshop, Newport, Rhode Island, June 25-26, 1996.

R. Quinn gave an invited seminar in the Dept. of Electrical Engineering and Applied Physics, Case Western Reserve University, Oct., 1996.

R. Ritzmann gave an invited talk at the ISAT Meeting on "Cost-Effective, Capable and Configurable Multiple Robots", Carnegie-Mellon University, June, 1996.

R. Ritzmann gave an invited seminar at Ohio University, June, 1996.

Robot III: CAD drawings of cockroach-like robot

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This performance report describes progress over the last 6 months in 3 areas: robotics, physiology and analysis of evolved neural circuits.

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